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Space Environmental Stability of Tedlar with Multi-Layer Coatings: Space Simulation Testing Results

20 August 2000

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Michael S Zambrana

Michael Zambrana
SMC/AXE

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13. ABSTRACT (*Maximum 200 words*)

Cloud White Tedlar with a multi-layer, thin-film coating on the surface applied by Optical Coatings Laboratory, Inc. (OCLI) is being investigated for potential spacecraft applications. Space environment exposure tests have been performed on a variety of samples exposed to simulated Low Earth Orbit (LEO) and Geosynchronous Orbit (GEO) conditions. The Space Environmental Effects Chamber used to provide the simulation of the LEO and GEO space environment contains a 2500-W xenon arc lamp for long-wavelength ultraviolet (UV) and a 150-W deuterium arc lamp for vacuum UV radiation. Beam sizes are a nominal 10 in. x 12 in. for long-wavelength UV and 7 in. x 7 in. for vacuum UV. The electron beam is about 14 in. x 14 in. with a beam energy variable from 5 keV to 120 keV. All beams are confocal. The large beam area allows multiple samples to be exposed and compared during a test.

Several tests have been performed for at least 2500 equivalent sun-hours. The initial value for solar absorptance of the 0.002-in. Cloud White Tedlar film was 0.12, while the multi-layer-coated Cloud White Tedlar was 0.09. After a five-year solar UV exposure, the solar absorptance values were 0.32 and 0.10, respectively. The presence of the coating provides excellent stability to the solar UV compared to uncoated Tedlar.

Electron depth dose curves have been calculated for a LEO orbital environment of 410 nmi and for a GEO orbit. These curves are presented along with the selected simulation electron energies and fluences to replicate the expected on-orbit exposure in the coated Tedlar material. Electron irradiations corresponding to LEO and GEO orbits were then performed. All samples were removed for solar absorptance end-of-life measurements. Data are presented for the coated Tedlar material for both LEO and GEO orbital exposures. The multi-layer coating on Tedlar provides protection from the damaging portion of the UV solar spectrum and would provide protection from the atomic oxygen environment as well. The material is very stable for LEO environments but does degrade in GEO exposure conditions for the multi-layer coating configuration studied.

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Preface

This work was presented in a poster session at the 8th International Symposium on "Materials in a Space Environment" and 5th International Conference on "Protection of Materials and Structures from the LEO Space Environment," Arcachon, France 5–9 June 2000. The authors would like to express their appreciation for the cooperation and helpful discussions with Dr. James Barrie of the Space Materials Laboratory of The Aerospace Corporation and Dr. Fred Van Milligan of Optical Coating Laboratory, Incorporated, Santa Rosa, California. Support for this work through SMC Contract F04701-00-C-0009 is gratefully acknowledged.

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1. Introduction

Tedlar is a polyvinyl fluoride film produced by E. I. DuPont de Nemours & Co. (Inc.) with a variety of additives that can be introduced to produce different properties. The designation code of TWH is for a white Tedlar film, and a TCW designation is indicative for a Cloud White version that has a lower solar absorptance (is a whiter material). The full designation for these products, for example, TCW20BE3, identifies color, thickness, surface finish, gloss, and type of elongation properties.

Cloud White Tedlar with a multi-layer, thin-film coating on the surface applied by Optical Coating Laboratory, Inc. (OCLI) is being investigated for a number of potential spacecraft applications. A space environment exposure test has been performed on a variety of samples exposed to simulated Low Earth Orbit (LEO) and Geosynchronous Orbit (GEO) conditions. The final portion of the test was performed to represent 10-year GEO environmental exposure on a subset of samples from the LEO test. This report addresses the samples exposed to GEO conditions.

The first portion of the test exposed the samples to an environment corresponding to five years at a LEO orbit of 410 nmi and an inclination of 57°. All samples were removed for LEO solar absorptance end-of-life measurements. The exposure then continued to 10-year GEO conditions (19,270 nmi) for the remaining samples. Solar absorptance at end-of-life for the GEO samples was then measured.

2. Experimental

The Space Environmental Effects Chamber (Figure 1) used to provide the simulation of the LEO and GEO space environment contains a 2500-W xenon arc lamp for long-wavelength ultraviolet (UV) (230–400 nm) and a 150-W deuterium arc lamp for vacuum ultraviolet (VUV) radiation (115–200 nm). Beam sizes are a nominal 10 in. x 12 in. for long-wavelength UV and 7 in. x 7 in. for VUV. The UV beams have a uniformity within 50% but contain small central hot spots. The electron beam is about 14 in. x 14 in. and is more uniform at about 10%. The beam energy is variable from 5 keV to 120 kV with flux roughly proportional to electron energy and a function of beam spot size (max. 1000 cm^2). All beams are confocal. The chamber is turbopumped and cryopumped, and the base pressure is currently 2×10^{-9} torr. The volume is roughly 400 liters with a sample table (12 in. x 48 in.) capable of temperature control from –150°C to +150°C, but kept at about 25°C for these tests. Computerized data acquisition is used for chamber diagnostics, which include several temperature and electron flux measurements.

The sample arrangement in the chamber is shown in Figure 2. The larger area represents the approximately 10 in. x 12 in. area covered by the xenon lamp. The area covered by the deuterium lamp is about 7 in. in diameter so it does not illuminate all samples in the LEO exposure. The solar cell is used as a diagnostic during the exposure to monitor the xenon lamp output. The Faraday cups monitor the electron flux at several locations during the electron exposure. An Optical Solar Reflector (OSR) is present as a check for any contamination that might condense during the test and potentially affect test results.

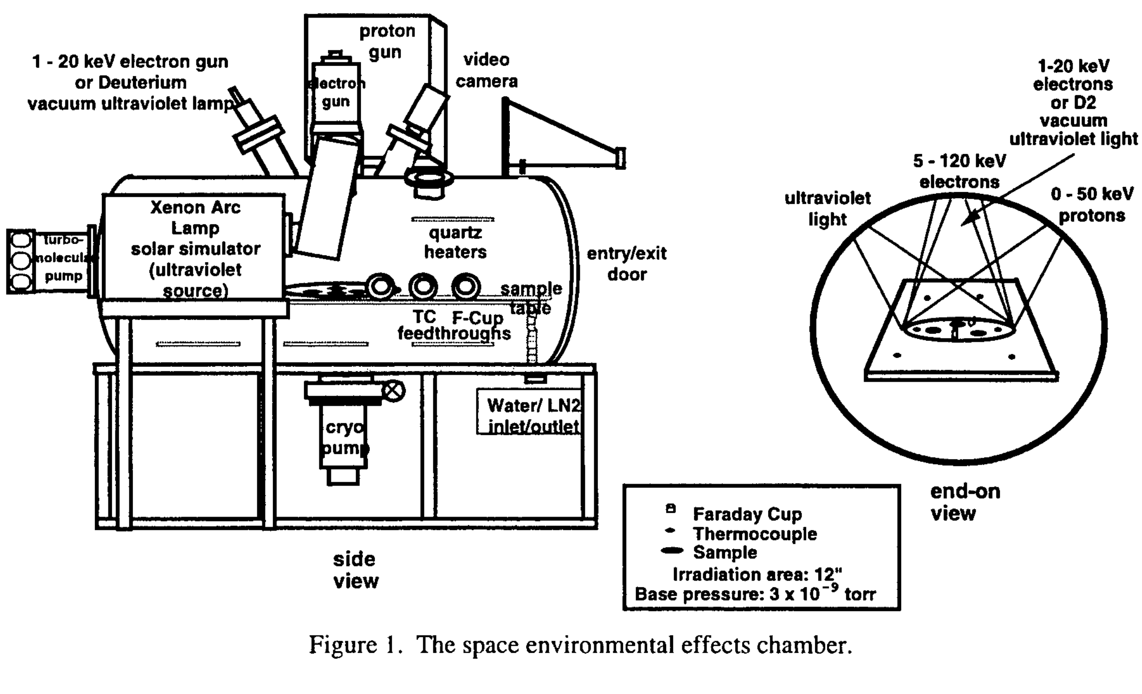

Figure 1. The space environmental effects chamber.

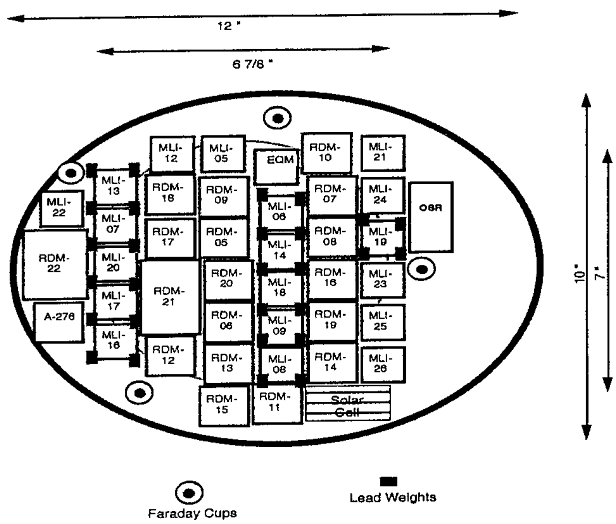

Figure 2. Test configuration for LEO exposure.

The electrons were added in the presence of Solar UV in the final stages of each exposure. The UV was not started until the chamber pressure was in the low to mid 10^{-8} torr region. After accumulation of 2554 equivalent UV sun-hours (982 h, at a solar intensity of 2.6 suns), electron doses were added to correspond to a LEO orbit of 410 nmi at a 57° inclination. These fluences are based on predicting the depth-dose electron profile in Tedlar for the assumed orbit using AE8 maximum predictions of electron fluences. The best set of reasonable conditions using the set energies of the electron gun on the chamber were chosen to match the depth-dose profile via a linear combination of multiple energies. The prediction curves are shown in Figure 3 for Low Earth Orbit Exposure and Figure 4 for Geosynchronous Orbit. The electron exposures were performed starting with the highest energy first and progressing successively to lower energies. The LEO test was performed with an electron current of about 0.1 nA/cm^2, corresponding to 6.25×10^8 electrons/s-cm^2. This level is typical of the current expected on orbit, although it fluctuates dramatically.

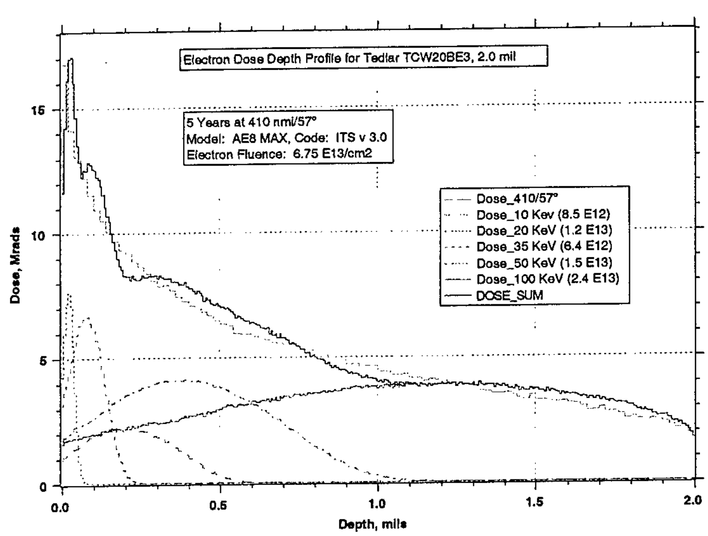

Figure 3. Predicted simulation dose profiles and orbital dose profile for LEO orbit.

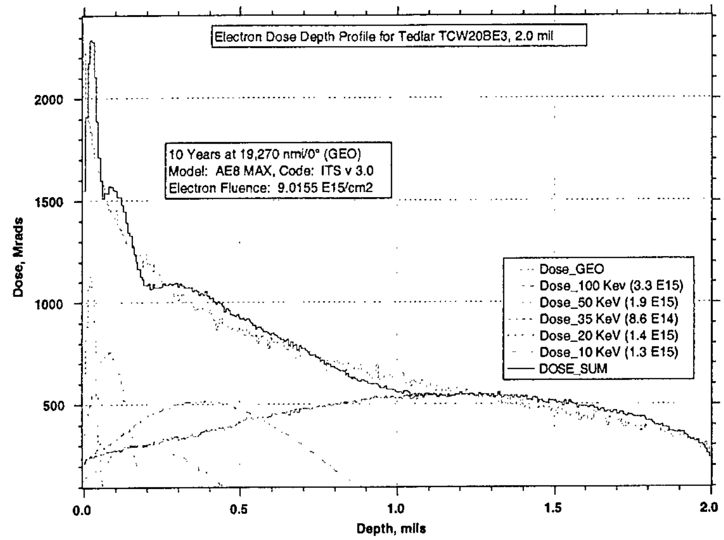

Figure 4. Predicted simulation dose profiles and orbital dose profile for GEO orbit.

After 2917 equivalent UV sun-hours, (1122 h, at a solar intensity of 2.6 suns), the LEO electron exposure was completed, and the LEO samples were removed. The UV exposure was then continued on the remaining samples up to 4282 sun-hours (1647 h, at a solar intensity of 2.6 suns) while the GEO electron dose was added. The GEO test was performed with an electron current of about 1 nA/cm^2 to more rapidly accumulate the desired fluence. This level of current could be expected on orbit, although it fluctuates dramatically. Throughout the entire exposure, the deuterium lamp was cycled on periodically (effectively 3.75 h per day) to accumulate approximately the same number of equivalent UV sun-hours as the xenon source. The deuterium source has been estimated to have an initial output of about 17 solar constants over its operating wavelength range, as compared to about 2.6 for the xenon source. The xenon source output is spectrally calibrated pretest using a calibrated spectral radiometer. Relative intensity over the sample area is mapped with a solar cell.

The following method was used to obtain the solar reflectance, transmittance, and absorptance. The Ultraviolet-Visible-Near Infrared (UV-VIS-NIR) diffuse hemispherical reflectance was measured on a Perkin-Elmer Lambda-9 equipped with a 6-in. Labsphere, Inc. Spectralon-coated integrating sphere. The reflectance measurements were made using a 240 nm/min. scan rate, 2 nm slit width, 0.5-s response, with the scan range being 250–2500 nm. The reflectance spectrum was background-corrected and referenced to a NIST 2019d White Tile Diffuse Reflectance Standard. The sample spectra were then normalized to the ASTM E490 solar air mass zero curve to obtain the solar absorptance/transmittance.

3. Results

During the exposure, photographs were taken periodically through the chamber viewports, and a short video was taken through an overhead viewport each day. The uncoated White Tedlar (TWH) samples were observed to turn brown during the initial LEO exposure to the UV. The Chemglaze A276 white paint sample also darkens, as expected from prior tests and from flight experience from the Long Duration Exposure Facility, for example. This material is included as a control sample for the exposure test. At the end of the LEO exposure, the changes in solar absorptance for the OCLI-coated Tedlar samples have been measured to be ~0.05 or less. The values are different for different samples due to the solar transmission of the 2-mil OCLI-coated Tedlar that is the outer layer of each sample. The differing underlying layers result in different solar properties. The measurement data is presented in Table 1.

The solar absorptance and transmittance data in Table 1 are consistent with the visual observations. The solar absorptance of the OCLI-coated TCW20BE3 has increased significantly with the GEO exposure (~6X over LEO). Again, the variations from sample to sample are due to effects of the underlying layers. The post-test solar absorptance was lowest for samples MLI-21 and MLI-22 with two underlying layers of Cloud White Tedlar (TCW). The most degradation appears to be for the case with two layers of White Tedlar (TWH) as the underlying layers. Figure 5 shows the changes in reflectance of one sample for the LEO and GEO exposures.

Table 1. Solar Absorptance and Transmittance Data

				LEO			
Sample #	**Pretest ρ**	**Pretest τ**	**Pretest α**	**Posttest ρ**	**Posttest τ**	**Posttest α**	**Delta α**
RDM 03	0.82		0.18	0.817		0.183	0.003
RDM 22	0.813		0.187	0.763		0.237	0.05
MLI 03	0.633	0	0.367	0.633		0.367	0
MLI 21	0.822	0.024	0.154	0.791	0.026	0.183	0.029
MLI 22	0.821	0.029	0.15	0.784	0.031	0.185	0.035
MLI 23	0.782	0.003	0.215	0.728	0.003	0.269	0.054
MLI 24	0.774	0.003	0.223	0.733	0.003	0.264	0.041
MLI 25	0.781	0	0.219	0.74	0	0.26	0.041
MLI 26	0.787	0	0.213	0.742	0	0.258	0.045
A 276	0.694	0	0.306	0.522	0	0.478	0.172
OSR	0.935	0	0.065	0.909	0	0.091	0.026

Sample #	Pretest ρ	Pretest τ	Pretest α	GEO Posttest ρ	Posttest τ	Posttest α	Delta α
RDM 03	0.82		0.18	0.818		0.182	0.002
RDM 22	0.813		0.187	0.523		0.477	0.29
MLI 03	0.633	0	0.367	0.633		0.367	0
MLI 21	0.822	0.024	0.154	0.547	0.019	0.434	0.28
MLI 22	0.821	0.029	0.15	0.543	0.012	0.445	0.295
MLI 23	0.782	0.003	0.215	0.469	0.001	0.53	0.315
MLI 24	0.774	0.003	0.223	0.458	0.001	0.541	0.318
MLI 25	0.781	0	0.219	0.494	0	0.506	0.287
MLI 26	0.787	0	0.213	0.491	0	0.509	0.296
A 276	0.694	0	0.306	0.378	0	0.622	0.316
OSR	0.935	0	0.065	0.904	0	0.096	0.031

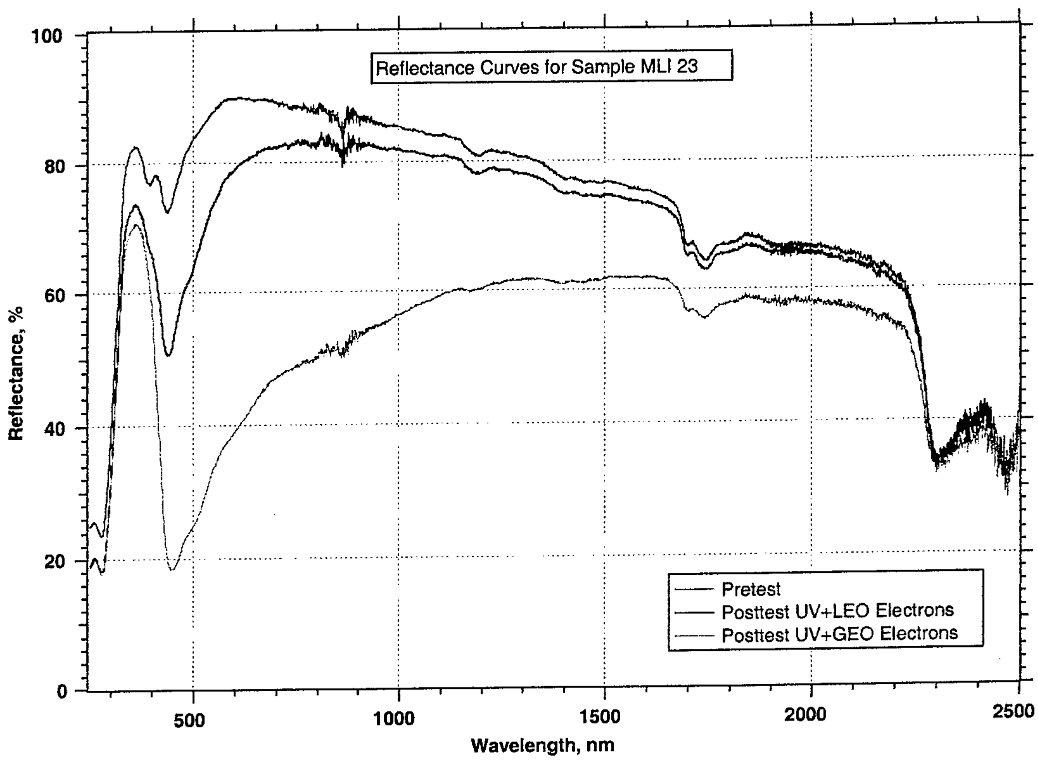

Figure 5. Reflectance curves for coated Tedlar sample.

4. Conclusion

The OCLI-coated Tedlar seems to be very stable for use at LEO orbits compared to other white thermal control materials. The End-of-Life for Ultraviolet exposure only was 0.22 and with LEO electron exposure, 0.24. The Low-Alpha coating reflects the Vacuum Ultraviolet radiation and prevents darkening of the underlying Cloud White Tedlar that would occur with solar radiation. The change in solar absorptance of 0.47 for the GEO exposure of the OCLI-coated Tedlar (0.47) was larger than expected. . A plot of the change in solar absorptance as a function of exposure is shown in Figure 6. For GEO orbits, the amount of degradation should be assessed in order to determine whether this effect results in unacceptable temperature at end-of-life conditions. Future work will involve the modeling of the plasma environment present at GEO and the laboratory simulation of this dose together with the trapped electron environment. Low-energy proton effects are also being studied.

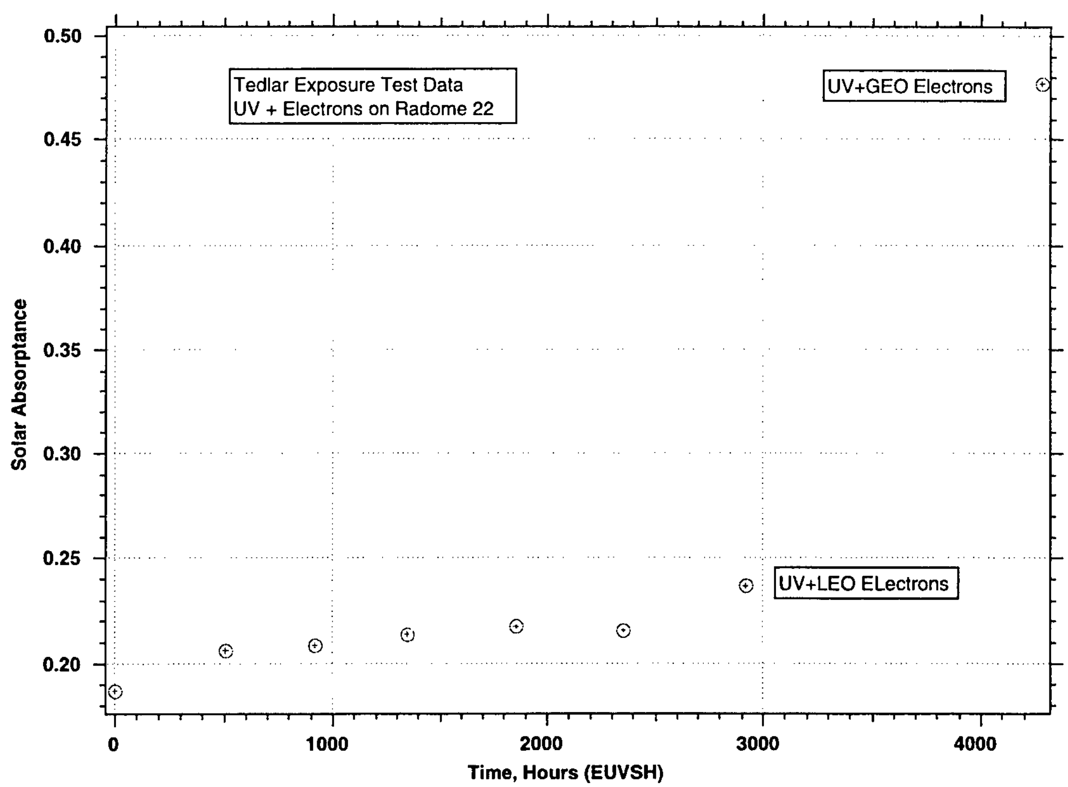

Figure 6. Solar absorptance degradation curve for coated Tedlar sample.

The following are the Charts for the Poster Presentation of

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Dr. Wayne Stuckey
Dr. Michael Meshishnek

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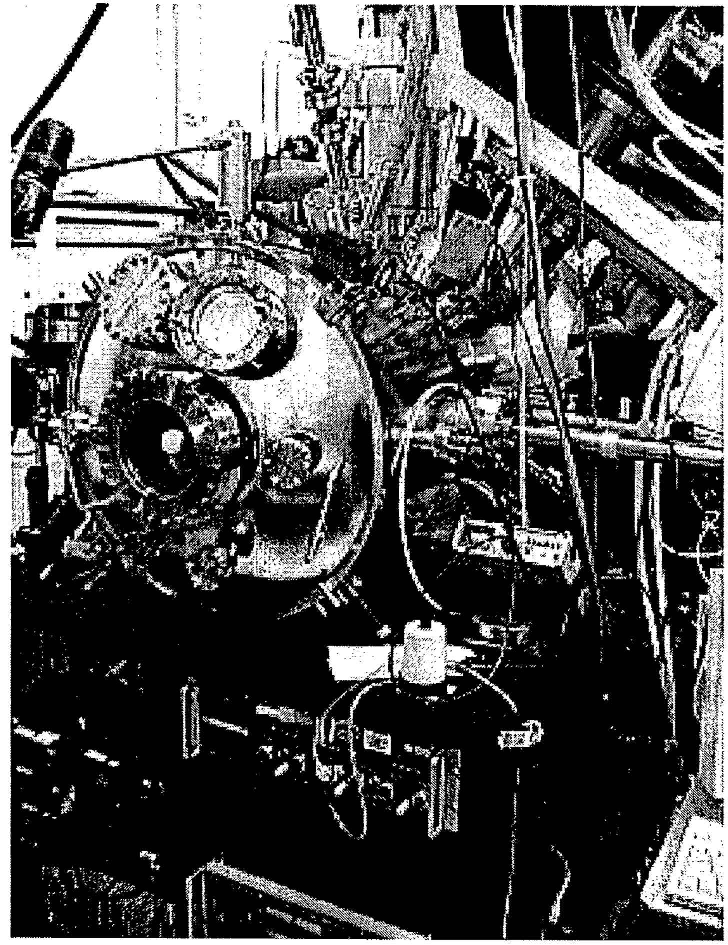
Space Environmental Effects Testing

CAPABILITIES

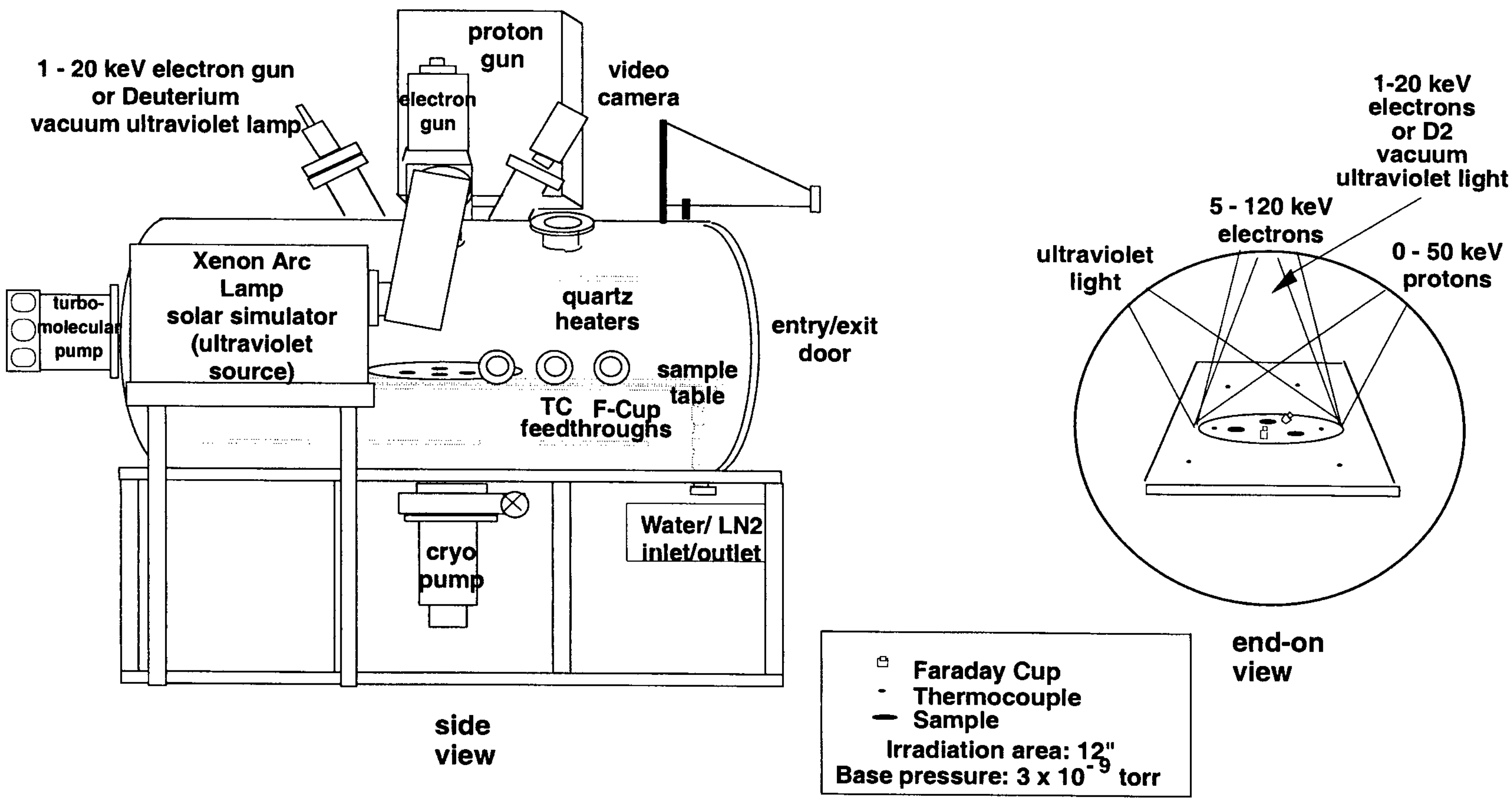
- Orbit specific radiation modeling
- Thermal-vacuum testing
- Solar ultraviolet and electron irradiation
- Proton irradiation
- Optical properties measurements

UTILIZATION

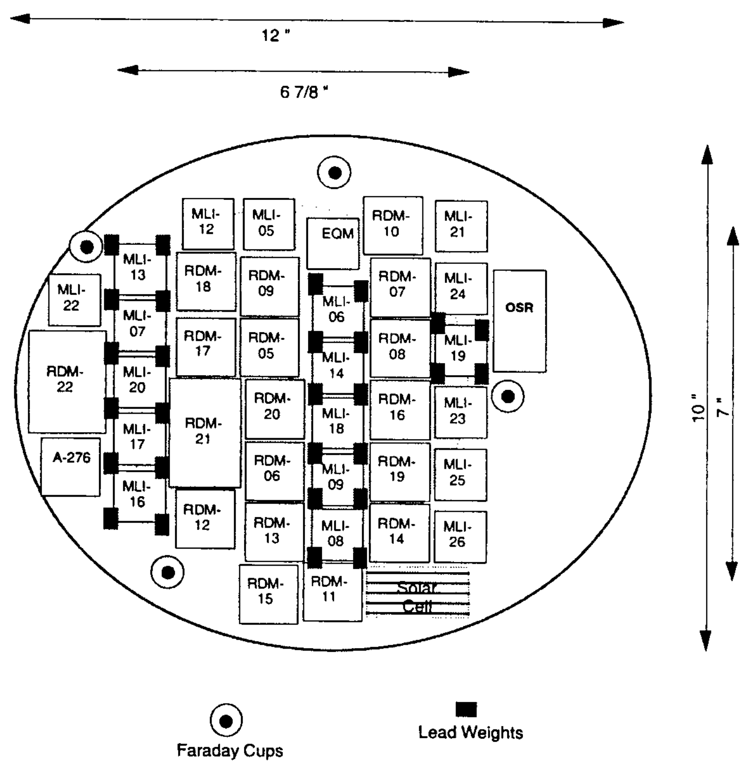
- Irradiation of coated polymers for MLI blankets and radomes
- Radiation testing of optical sensor dome
- Evaluation of polymer films for inflatable structures



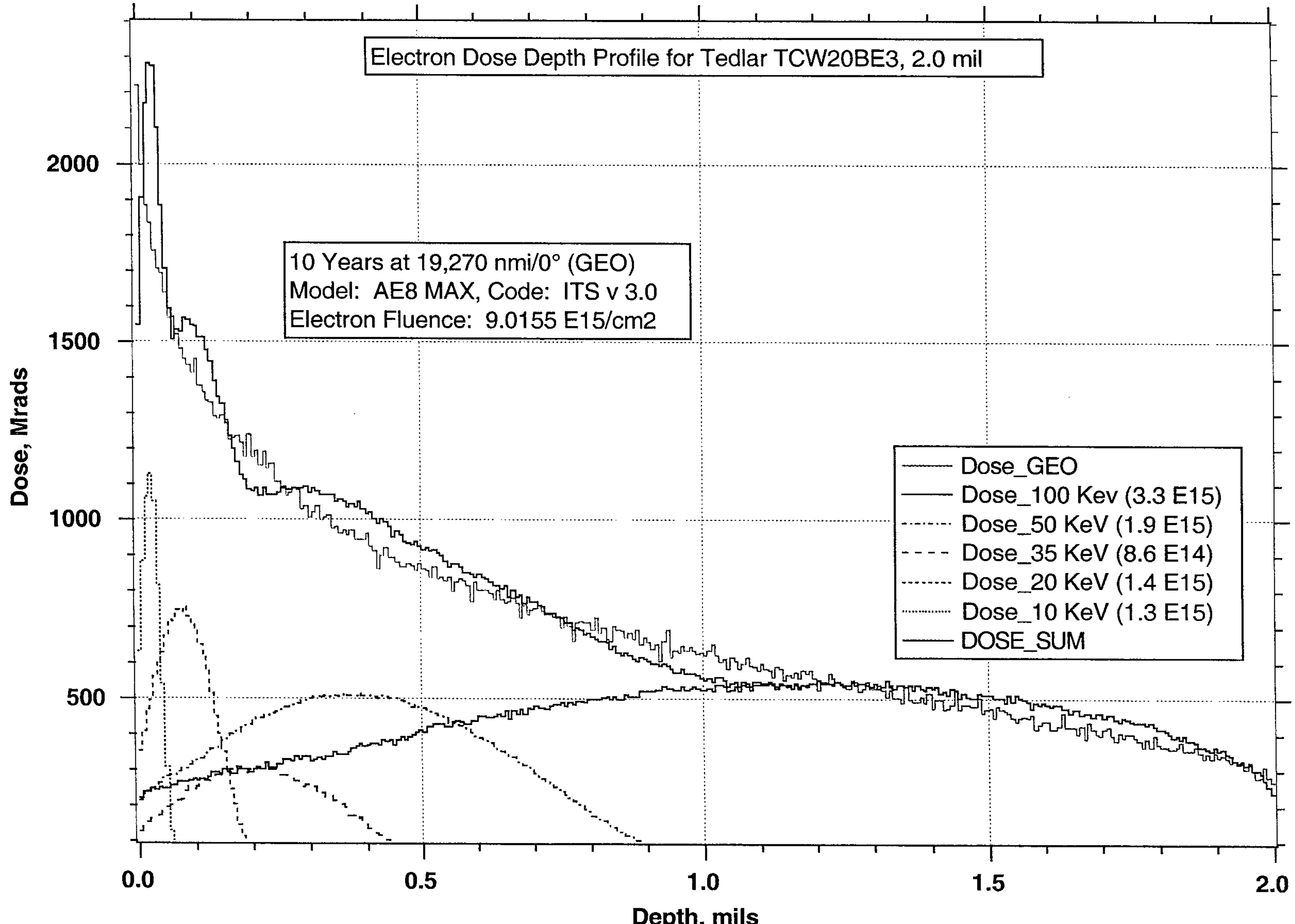
Space Environment Effects Test Chamber



Sample Configuration for Exposure



Predicted simulation dose profiles and orbital dose profile for GEO orbit



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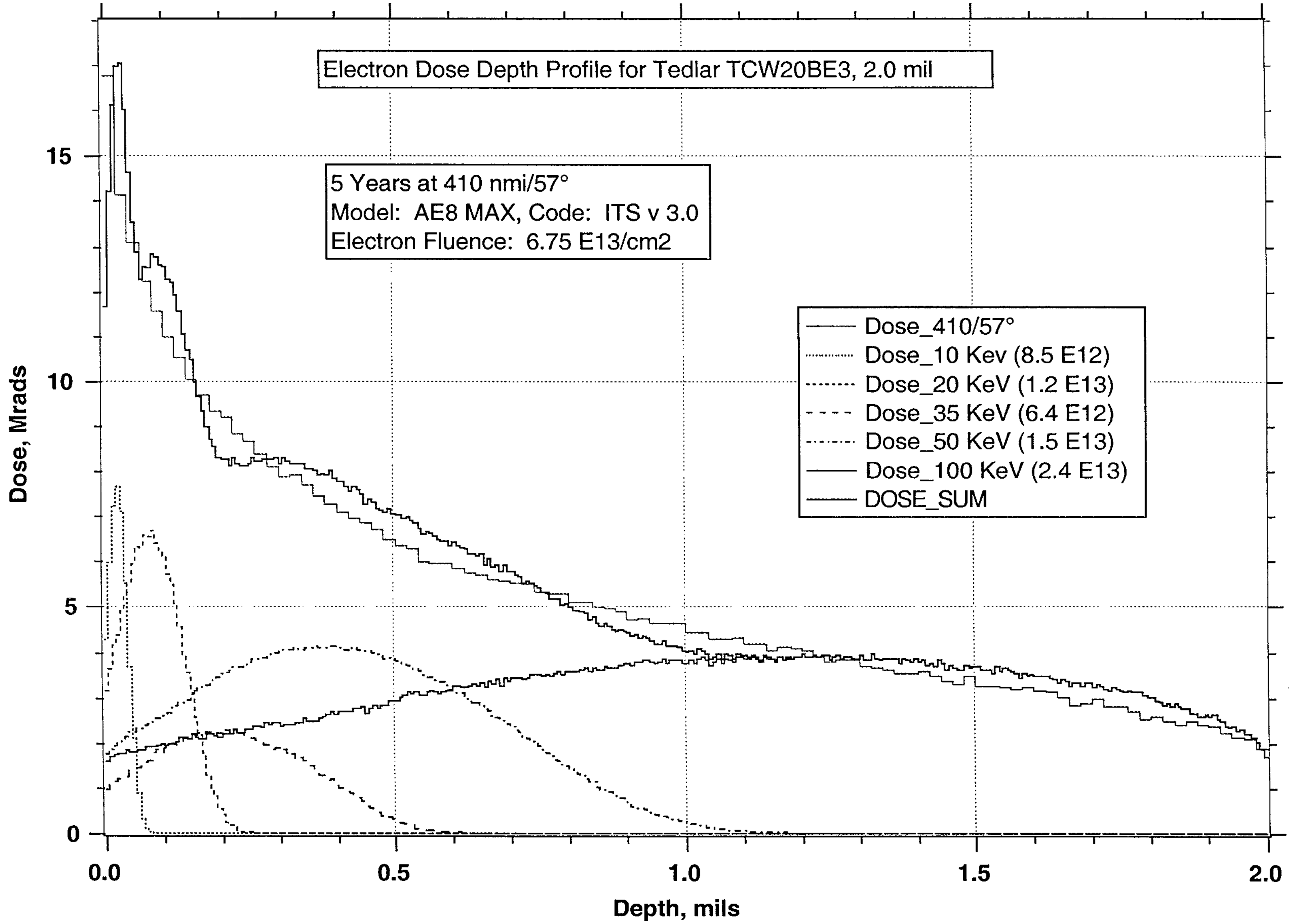
Predicted simulation dose profiles and orbital dose profile for LEO orbit



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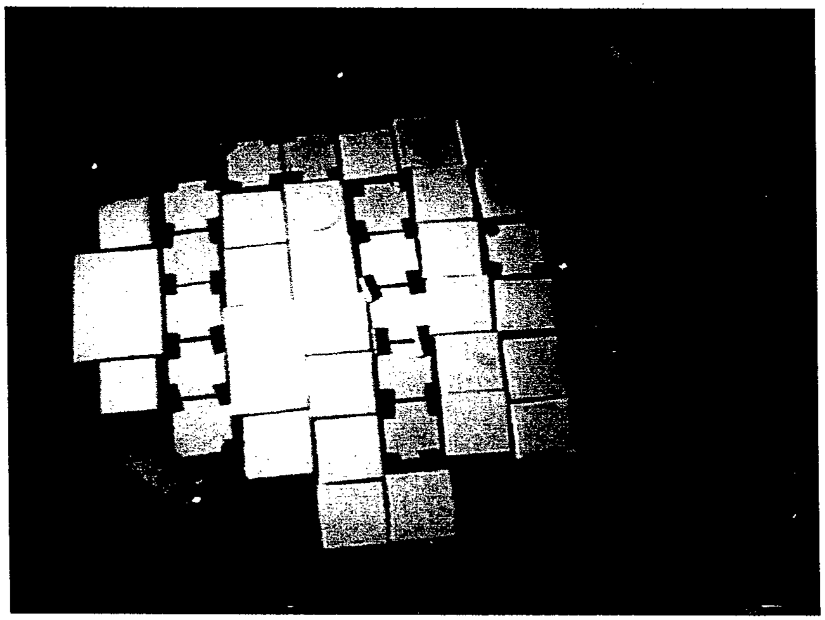
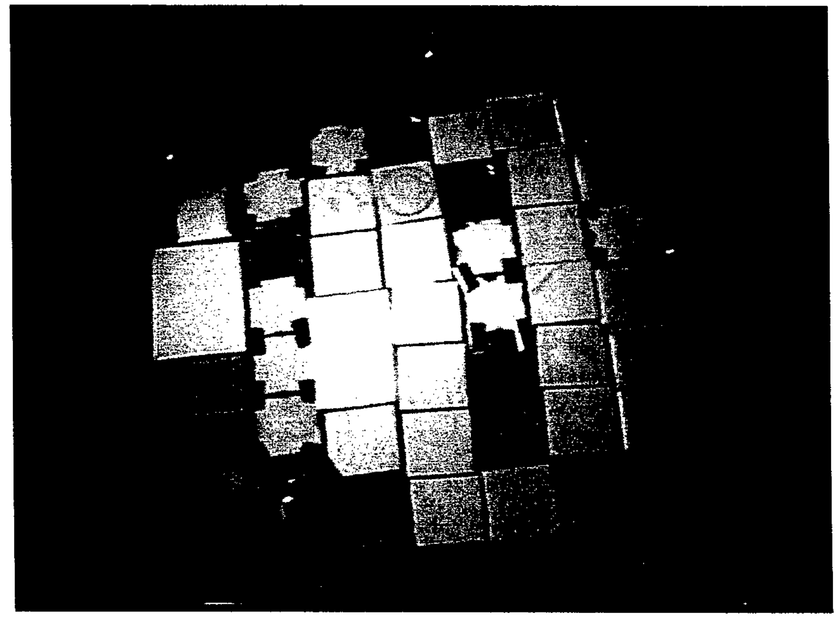
Photographs

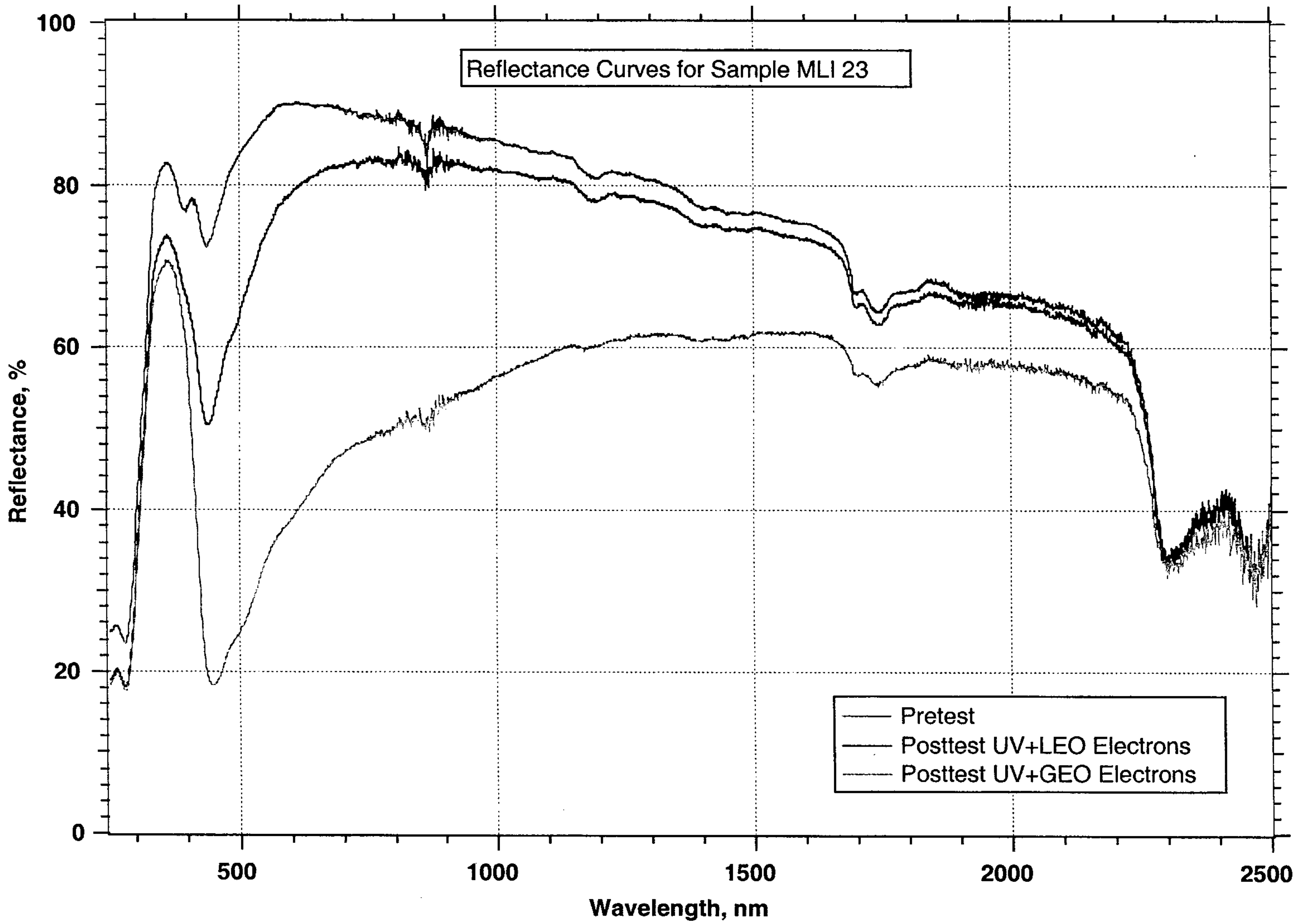


Beginning of Test



End of Test

Reflectance Curves for Coated Tedlar Sample



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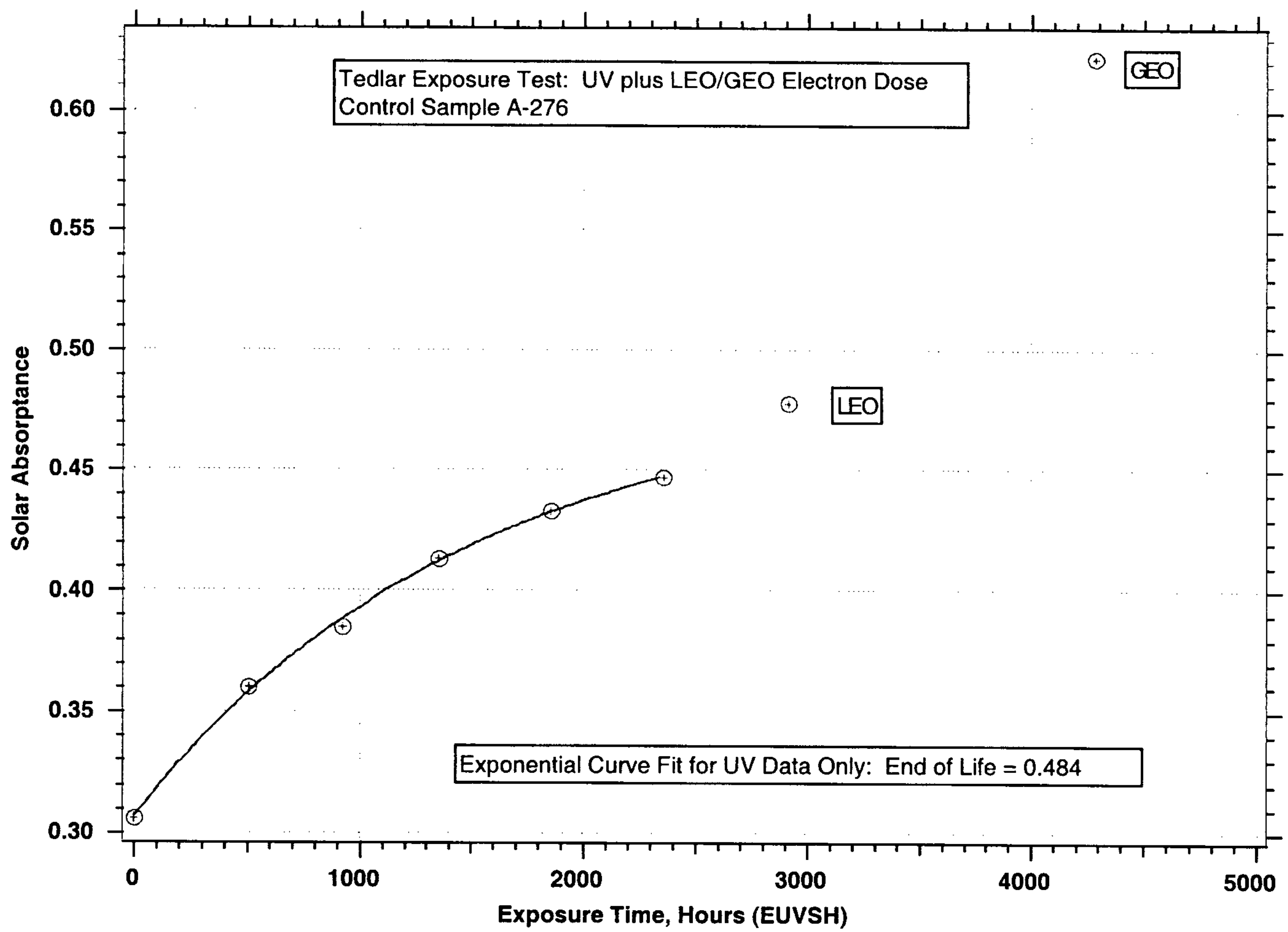
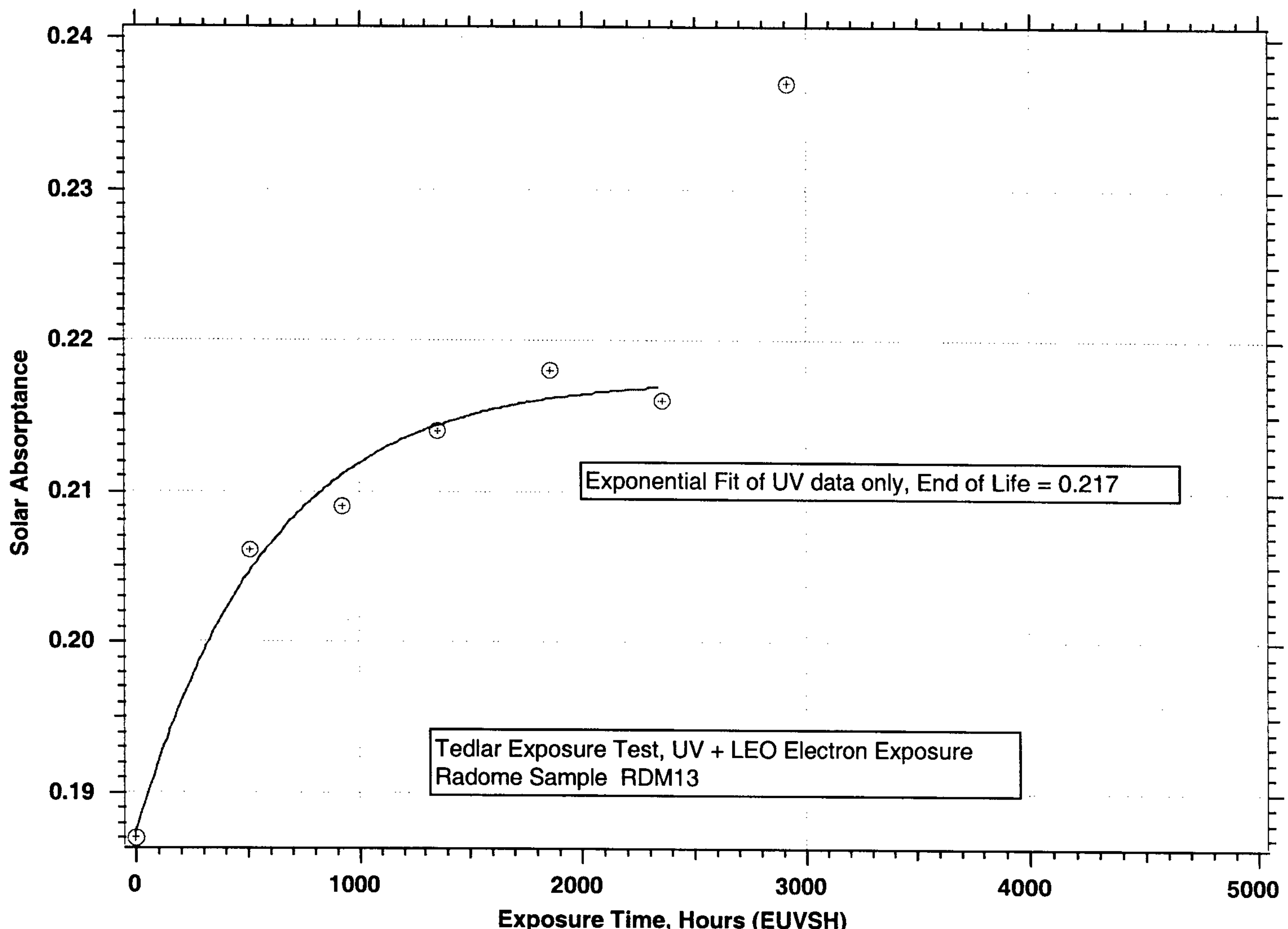
Solar Absorptance and Transmittance Data for LEO

Sample	OuterMaterial	Description	Pretest_r	Pretest_t	Pretest_a	Posttest_r	Posttest_t	Posttest_a	Delta_a
EQM		OCLI/TCW20BE3/Rohacell Foam	0.816	0.004	0.18	0.769	0.004	0.227	0.047
RDM-01	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center	0.815	0.002	0.183	0.817	0.002	0.181	-0.002
RDM-02	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center	0.818	0.002	0.18	0.821	0.002	0.177	-0.003
RDM-03	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center	0.82		0.18	0.817		0.183	0.003
RDM-04	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center	0.818		0.182	0.818		0.182	0
RDM-05	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center	0.819		0.181	0.768		0.232	0.051
RDM-06	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center	0.814		0.186	0.765		0.235	0.049
RDM-07	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Edge	0.818		0.182	0.768		0.232	0.05
RDM-08	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Corner	0.811	0.003	0.186	0.759	0.003	0.238	0.052
RDM-09	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Patch	0.757	0.014	0.229	0.697	0.01	0.293	0.064
RDM-10	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Patch	0.758	0.012	0.23	0.711	0.01	0.279	0.049
RDM-11	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center	0.819		0.181	0.78		0.22	0.039
RDM-12	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center	0.819		0.181	0.772		0.228	0.047
RDM-13	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - Radome w/wrinkle	0.813		0.187	0.763		0.237	0.05
RDM-14	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - Radome w/wrinkle	0.814		0.186	0.77		0.23	0.044
RDM-15	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center - Damaged	0.815		0.185	0.774		0.226	0.041
RDM-16	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center - Damaged	0.818		0.182	0.769		0.231	0.049
RDM-17	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome Center - Damaged	0.817		0.183	0.765		0.235	0.052
RDM-18	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome - Bubbled area	0.819		0.181	0.775		0.225	0.044
RDM-19	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - ILU Radome - Bubbled area	0.816	0.003	0.181	0.768	0.003	0.229	0.048
RDM-20	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - Control Radome	0.815	0.003	0.182	0.766	0.003	0.231	0.049
RDM-21	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - Radome w/wrinkle	0.811		0.189	0.757		0.243	0.054
RDM-22	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam - Radome w/wrinkle	0.813		0.187	0.763		0.237	0.05
EQM T/V	OCLI/TCW20BE3	OCLI/TCW20BE3/Rohacell Foam							
MLI-03	TWH15BS3	Tedlar Film	0.633	0	0.367	0.633		0.367	0
MLI-04	TWH15BS3	Tedlar Film	0.631	0	0.369	0.631		0.369	0
MLI-05	TWH15BS3	Tedlar Film	0.633	0	0.367	0.483		0.517	0.15
MLI-06	TWH15BS3	Tedlar Film	0.633	0	0.367	0.479		0.521	0.154
MLI-07	TWH15BS3	Tedlar Film	0.633	0	0.367	0.468		0.532	0.165
MLI-08	TWH15BS3	Tedlar Film	0.634	0	0.366	0.473		0.527	0.161
MLI-09	TWH15BS3	Tedlar Film	0.632	0	0.368	0.471		0.529	0.161
MLI-10	TWH15BS3	Tedlar Film							
MLI-11	TWH15BS3	Tedlar Film	0.637		0.363				
MLI-12	TWH15BS3	Tedlar Film	0.686		0.314	0.66		0.34	0.026
MLI-13	TWH15BS3	Tedlar Film	0.685		0.315	0.666		0.334	0.019
MLI-14	TWH15BS3	Tedlar Film	0.69		0.31	0.657		0.343	0.033
MLI-15	TWH15BS3	Tedlar Film	0.638		0.362				
MLI-16	TWH15BS3	Tedlar Film	0.701		0.299	0.674		0.326	0.027
MLI-17	TWH15BS3	Tedlar Film	0.698		0.302	0.668		0.332	0.03
MLI-18	TWH15BS3	Tedlar Film	0.687		0.313	0.654		0.346	0.033
MLI-19	TWH15BS3	Tedlar Film	0.686		0.314	0.664		0.336	0.022
MLI-20	TWH15BS3	Tedlar Film	0.7		0.3	0.674		0.326	0.026
MLI-21	OCLI/TCW20BE3	2 mil OCLI-Coated TCW20BE3 Tedlar - Inner Layers: 2 - 2 mil layers of uncoated CW Tedlar, with scrim cloth	0.822	0.024	0.154	0.791	0.026	0.183	0.029
MLI-22	OCLI/TCW20BE3	2 mil OCLI-Coated TCW20BE3 Tedlar - Inner Layers: 2 - 2 mil layers of uncoated CW Tedlar, with scrim cloth	0.821	0.029	0.15	0.784	0.031	0.185	0.035
MLI-23	OCLI/TCW20BE3	2 mil OCLI-Coated TCW20BE3 Tedlar - Inner Layers: 2 - 2 mil layers of uncoated CW Tedlar, with scrim cloth	0.782	0.003	0.215	0.728	0.003	0.269	0.054
MLI-24	OCLI/TCW20BE3	2 mil OCLI-Coated TCW20BE3 Tedlar - Inner Layers: 2 - 2 mil layers of uncoated CW Tedlar, with scrim cloth	0.774	0.003	0.223	0.733	0.003	0.264	0.041
MLI-25	OCLI/TCW20BE3	2 mil OCLI-Coated TCW20BE3 Tedlar - Inner Layers: 2 - 2 mil layers of uncoated CW Tedlar, with scrim cloth	0.781	0	0.219	0.74	0	0.26	0.041
MLI-26	OCLI/TCW20BE3	2 mil OCLI-Coated TCW20BE3 Tedlar - Inner Layers: 2 - 2 mil layers of uncoated CW Tedlar, with scrim cloth	0.787	0	0.213	0.742	0	0.258	0.045
A 276			0.694	0.306	0.522	0	0.478	0.172	
OSR			0.935	0	0.065	0.909	0	0.091	0.026

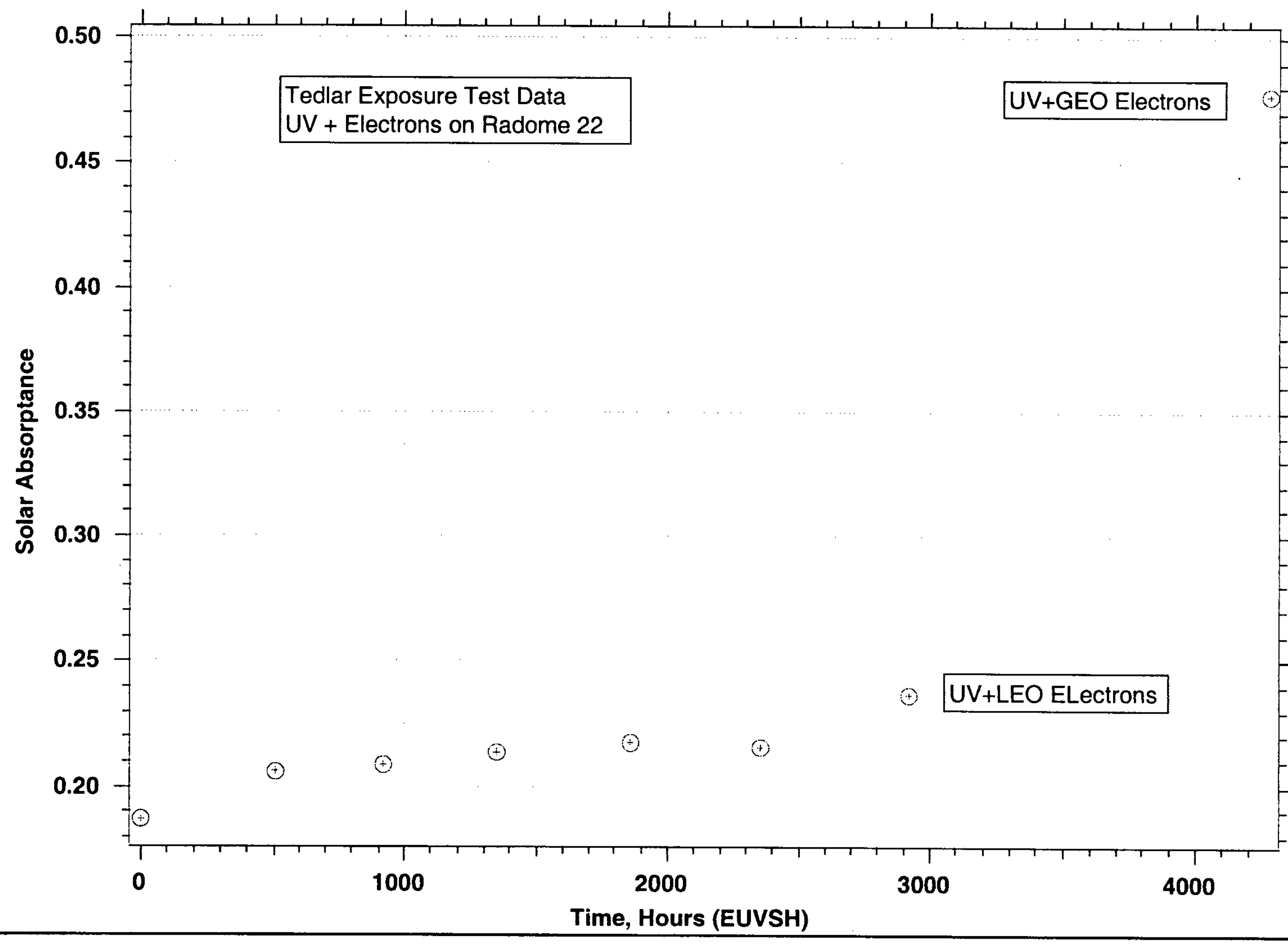
A–276 Solar Absorptance



Coated Tedlar Solar Absorptance (LEO)



Coated Tedlar Solar Absorptance (GEO)



Summary

- Solar Absorptance of Uncoated Tedlar Increases from Solar Ultraviolet Radiation
- Multi-Layer Dielectric Coatings provide stability to Degradation from Solar Radiation
- Electron Radiation increases Solar Absorptance

- Typical Values for 2 mil Cloud White Tedlar on White Foam

  - Beginning of Life 0.18
  - End of Life
    - UV Only 0.22
    - LEO 0.24
    - GEO 0.47

TECHNOLOGY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Technology Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual organizations:

Electronics Technology Center: Microelectronics, VLSI reliability, failure analysis, solid-state device physics, compound semiconductors, radiation effects, infrared and CCD detector devices, data storage and display technologies; lasers and electro-optics, solid state laser design, micro-optics, optical communications, and fiber optic sensors; atomic frequency standards, applied laser spectroscopy, laser chemistry, atmospheric propagation and beam control, LIDAR/LADAR remote sensing; solar cell and array testing and evaluation, battery electrochemistry, battery testing and evaluation.

Mechanics and Materials Technology Center: Evaluation and characterizations of new materials and processing techniques: metals, alloys, ceramics, polymers, thin films, and composites; development of advanced deposition processes; nondestructive evaluation, component failure analysis and reliability; structural mechanics, fracture mechanics, and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle fluid mechanics, heat transfer and flight dynamics; aerothermodynamics; chemical and electric propulsion; environmental chemistry; combustion processes; space environment effects on materials, hardening and vulnerability assessment; contamination, thermal and structural control; lubrication and surface phenomena.

Space and Environment Technology Center: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; infrared surveillance, imaging, remote sensing, and hyperspectral imaging; effects of solar activity, magnetic storms and nuclear explosions on the Earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation, design fabrication and test; environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes.

Center for Microtechnology: Microelectromechanical systems (MEMS) for space applications; assessment of microtechnology space applications; laser micromachining; laser-surface physical and chemical interactions; micropropulsion; micro- and nanosatellite mission analysis; intelligent microinstruments for monitoring space and launch system environments.

Office of Spectral Applications: Multispectral and hyperspectral sensor development; data analysis and algorithm development; applications of multispectral and hyperspectral imagery to defense, civil space, commercial, and environmental missions.